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Analysis of stresses in two-dimensional models of normal and neuropathic feet

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Abstract—*A two-dimensional model of the normal foot skeleton, which includes cartilages and ligaments, is used in this analysis of stresses during three quasi-static walking phases: heel-strike, mid-stance and push-off. It is found that in all the walking phases the maximum values of principal stresses occur in the dorsal anterior region of the talus, whereas the highest stress occurs in the push-off phase. The model is used for the simulation of muscle paralysis and its effect on the distribution of principal stresses. Subsequently, the model is used to analyse stresses in the deformed feet of three leprosy patients with complete paralysis of certain muscles. The results demonstrate that both the shape of the foot and the type of muscle paralysis contribute to the development of high stresses in different regions of the foot. These high stresses in regions with reduced mechanical strength could be one of the important factors in the process of tarsal disintegration in leprosy.*

Keywords—*Finite element, Neuropathic feet, Stress analysis, Two-dimensional foot model*

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1 Introduction

THE INTERNAL stress developed in the foot skeleton cannot be measured directly *in vivo* or *post mortem*. However, using a modelling procedure such stresses can be predicted. We have previously developed two-dimensional single bone models of the foot to study the stress patterns in three quasi-static situations of the foot, representing heel-strike, mid-stance and push-off (PATIL *et al.*, 1993a). We have also developed a two-dimensional model of a normal foot (in mid-stance) that enabled simulation of articulations (joints) step-wise to analyse concurrent stress patterns (PATIL *et al.*, 1993b). In those studies only one muscle was active in each of the three positions: the tibialis anterior (TA) during heel-strike and the triceps surae (TS) during mid-stance and push-off (PATIL *et al.*, 1993a;b).

In this study, we report on the effects on the stress states of this model in mid-stance when more active muscles are included. The same model is used to calculate stress patterns in two other quasi-static situations, heel-strike and push-off, and in situations where one or more muscles are assumed to be paralysed due to accidents or diseases like leprosy or diabetes. In an attempt to explain tarsal disintegration, the combined effects of a deformed foot with changed geometries and muscle paralysis are investigated.

The stress calculations are carried out using GIFTS, a finite-element software package*, which is suited for linear material behaviour and small displacements.

2 Model

2.1 *Normal foot*

Many muscles responsible for foot movement (but not most of them) have very long tendons. They are located in the lower leg and produce motion in the ankle joint (dorsal and plantar flexion), as well as in the tarsal joints (inversion and eversion) and in the metatarsophalangeal joints (flexion and extension of the toes). As they are attached to many of the foot bones, they also contribute to stresses in the bones.

The guide point for muscles going around medial pulley (point P_1) represents the sustentaculum tali, which is the medial part of the calcaneus (Fig. 1). With its groove underneath, it acts as a pulley for the tibialis posterior (TP) and flexor hallucis longus (FHL). A less prominent but similar bony protuberance, with a similar location at the lateral side of the calcaneus, serves the peroneous longus (PL). It is an effect at the lateral surface of the calcaneus, although the insertion of the PL is on the medially located first cuneiform. The PL crosses the foot at the plantar side.

All these muscles are guided by tendon sheaths attached to the described bony prominences. The extensor hallucis longus (EHL) and tibialis anterior (TA) are guided by a tendinous sling attached at P_2, a point located somewhat more proximal to the pulley's site of P_1. The various muscle forces (BASMAJIAN, 1978; INMAN *et al.*, 1981) that are active in the normal articulated foot model and the ankle joint force are shown in Fig. 1. Not all the muscles are active in each of the three quasi-static walking positions: heel-strike (HS), mid-stance (MS) and push-off (PO). For this 2-D model, only force components with an effect in the sagittal plane have been considered.

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* CASA/GIFTS Inc., Tucson, Arizona

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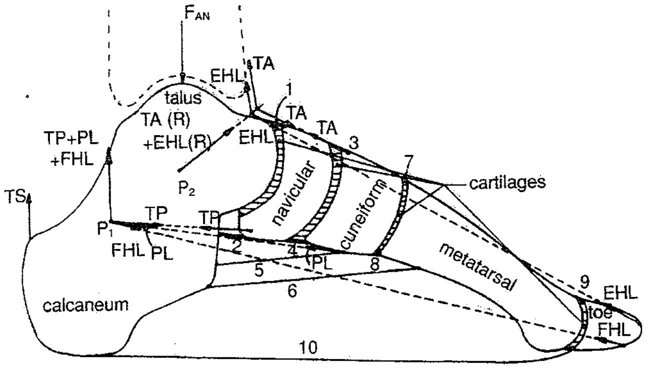

Fig. 1 *Muscle forces and ankle joint force acting on the two-dimensional model of the foot skeleton; P_1 = guide point for muscles going round medial pulley; P_2 = attachment point of slip guiding muscles EHL and TA; F_{AN} = ankle joint force; TS = tricep surae; PL = peroneous longus; FHL = flexor hallucis longus; TP = tibialis posterior; EHL = extensor hallucis longus; TA = tibialis anterior; 1–10 = ligaments*

Table 1 presents the active muscles and the magnitudes of their (mean) forces. The magnitudes of the ankle joint forces are obtained from previous work by Röhrl *et al.* (RÖHRL, 1984). The magnitudes of the muscle forces are obtained from previous work by Seireg and Arvikar and Calderale and Scelfo, and by using force equilibrium equations for the unknown muscle forces EHL in heel-strike and PL in the mid-stance and push-off position of the foot (SEIREG and ARVIKAR, 1975; CALDERALE and SCELFO, 1987).

In heel-strike, the foot is in dorsiflexion and the foot sole is inclined 30° with respect to the horizontal, whereas in push-off the foot is in plantar flexion and the inclination is 45° (BASMAJIAN, 1978; INMAN *et al.*, 1981). The actual geometry of the foot is obtained from a medial-lateral X-ray of a normal foot. The directions and the attachment points of the tendons are based on anatomical considerations (WILLIAMS *et al.*, 1989). Young's modulus and Poisson's ratio of the cartilages are taken as 10 MPa and 0·4, respectively, (SCHREPPERS *et al.*, 1990; BROWN *et al.*, 1980) and the corresponding values for bone are 7300 MPa and 0·3 (NAKAMURA *et al.*, 1981). The stiffness of each ligament is taken as 1500 N mm^{-1} (PATIL *et al.*, 1993b).

2.2 *Foot with paralysed muscles*

In this section foot modelling involves the use of an articulated foot model (see Section 2.1) in the analysis of stresses, simulating paralysis in muscles due to accidents, leprosy or diabetes. In heel-strike, if EHL is paralysed, it is assumed that the force in the remaining active muscle (TA) increases to maintain quasi-static force equilibrium, given the ankle joint force from Table 1. Similarly, when FHL and/or TP are paralysed in mid-stance or push-off, it is assumed that the most powerful muscle (triceps surae, TS) will generate a greater force to maintain equilibrium. In each of these cases (see Table 2) the forces in paralysed muscles are taken as zero.

Table 1 Magnitudes of bone and mean muscle forces in the walking phases heel-strike, mid-stance and push-off

	HS, N	MS, N	PO, N
tibialis anterior (TA)	500	—	—
extensor hallucis longus (EHL)	231	—	—
peroneous longus (PL)	—	350	134
flexor hallucis longus (FHL)	—	400	50
tibialis posterior (TP)	—	—	400
triceps surae (TS)	—	600	1100
ankle joint force, F_{AN}	1350 (2·25*W*)	2100 (3·5*W*)	3000 (5*W*)
reaction force at P_1, R_1	—	1025	865
reaction force at P_2, R_2	716	—	—

W = body weight of a normal person, here 600 N; muscle and reaction forces represent mean values; in the calculations they have been varied between 0·9 and 1·1 times the mean value

2.3 *Leprotic foot*

As leprosy patients have deformed feet in addition to a partial or complete paralysis of certain muscles, this analysis considers the shape of the foot (obtained from X-rays) and the muscle status (regarding conditions of paralysis) from clinical data. The foot model is applied to three leprosy patients, with feet in different stages of tarsal disintegration, for the analysis of stresses.

Fig. 2 shows the geometry of the right foot model, along with forces acting in the mid-stance phase of patient MLW. This patient has paralysed right foot dorsiflexors (TA and EHL) and FHL, and a portion of the navicular bone is emerging which appears to be chipped off at the upper part. An X-ray of the foot shows an early stage of tarsal disintegration. The loading of the model accounts for the paralysis of muscles.

The second patient KTD is in an intermediate stage of tarsal disintegration; he has completely paralysed right foot dorsiflexors (TA and EHL) and FHL, and extremely shortened metatarsals (his forefoot is virtually resting on the remains of

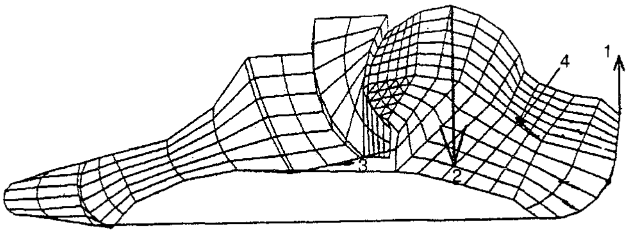

Fig. 2 *Two-dimensional model and the finite-element mesh in the deformed and paralysed foot of the leprotic patient MLW in mid-stance phase; forces in 1 = TS, 2 = FAN, 3 = PL, 4 = reaction force R_1 at the guide point P_1 due to PL*

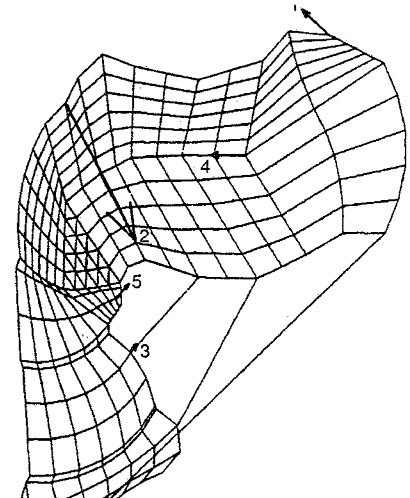

Fig. 3 *Two-dimensional model and the finite-element mesh in the deformed and paralysed foot of the leprotic patient KTD in push-off phase; forces in 1 = TS, 2 = FAN, 3 = PL, 4 = reaction force R_1 at the guide point P_1 due to PL and TP, 5 = TP*

Table 2 Magnitudes of bone and mean muscle forces in the active muscle during the simulated walking phases heel-strike, mid-stance and push-off with paralysed muscles

	HS_1, N	HS_2, N	MS_1, N	MS_2, N	PO_1, N	PO_2, N	PO_3, N	PO_4, N
TA	FP	*724*	—	—	—	—	—	—
EHL	*742*	FP	—	—	—	—	—	—
TP	—	—	—	—	400	FP	FP	FP
PL	—	—	FP	350	FP	134	FP	FP
FHL	—	—	400	FP	50	50	50	FP
TS	—	—	*874*	*920*	*1210*	*1440*	*1555*	*1596*
R_1	—	—	*522*	*507*	*676*	*252*	*63*	—
R_2	*696*	*724*	—	—	—	—	—	—

HS_1, HS_2, …, PO_4 = several simulations of walking phases with paralysed muscles. FP = fully paralysed, TA = tibialis anterior, EHL = extensor hallucis longus, TP = tibialis posterior, PL = peroneous longus, FHL = flexor hallucis longus, TS = triceps surae, R_1 = reaction force at pulley point 1, R_2 = reaction force at pulley point 2; calculated forces are *in italics*; other forces (ankle joint forces, muscle forces and bone reaction forces) are assumed to have the values in Table 1. — indicates an inactive muscle or absent reaction force

the metatarsal base). This is shown in Fig. 3, which provides the geometry of the foot in push-off phase, along with the muscle and ankle forces acting on the model.

The third patient KLPS is in an advanced stage of tarsal disintegration, with his left foot with a collapsed arch and portions of the cuneiform and metatarsals protruding. In the mid-foot region the foot has the shape of a rocker foot. The dorsiflexors and FHL are completely paralysed.

Table 3 presents the magnitudes of (mean) load values acting on the foot model for the three patients; these values are determined in the same way as in Section 2.2. To obtain an insight into the sensitivity of the stresses for load variations, calculations are carried out with variations of ± 10% in the mean value of the magnitudes of the muscle forces presented in Tables 1–3.

3 Results

3.1 *Normal foot*

The finite-element calculations of a 2-D model of a normal foot, with active muscles, show that in each quasi-static walking phase the dorsal anterior regions of the talus bordering the cartilage between the talus and the navicular have the highest maximal principal stress. Fig. 4 presents the von Mises stress contours during the push-off phase and shows the most highly stressed region.

The mean values of maximum principal stresses in the three phases (heel-strike, mid-stance and push-off) are in the ratio 1 : 1·5 : 3·25; in magnitude $26{\cdot}7 \pm 0{\cdot}4\ \mathrm{N\ mm^{-2}}$; $40{\cdot}5 \pm 2{\cdot}0\ \mathrm{N\ mm^{-2}}$ and $83{\cdot}5 \pm 0{\cdot}6\ \mathrm{N\ mm^{-2}}$. It is observed that in most parts of the model the principal stress in a point is compressive, although in the most highly stressed regions there is also a tensile component (especially in the anterior dorsal region of the talus).

3.2 *Foot with paralysed muscles*

The results presented here (except for TA paralysis where the most highly stressed region is the toe) indicate the changes in the maximum values of the principal stresses in the dorsal anterior region of the talus, compared with the corresponding normal mean values.

3.2.1 *Heel-strike position:* complete loss of the motor functions of the TA means that other extensors of the foot (EHL in our simplified model) need to deliver all the force needed for equilibrium. It is therefore not surprising that the upper toe region is now far more loaded than in a normal foot; the stresses in the toe region are 2·3 times higher than the corresponding normal value of $12{\cdot}6\ \mathrm{N\ mm^{-2}}$.

Table 3 Magnitudes of bone and mean muscle forces used in the simulated walking phases of three leprosy patients (MLW, KTD and KLPS)

	mid-stance		push-off		
	MLW, N	KTD, N	MLW, N	KTD, N	KLPS, N
FHL	FP	FP	FP	FP	FP
PL	350	350	66	133	FP
TP	–	–	400	400	FP
TS	795	170	1100	714	1596
R_1	*465*	*407*	*723*	*689*	

Ankle joint forces, muscle forces and bone reaction forces are assumed to be similar to those in Table 1; — indicates inactive muscle; due to muscle paralysis these patients have no heel-strike; mid-stance and push-off are similar in patient KLPS due to clinical muscle paralysis and the particular geometry of his rocker foot

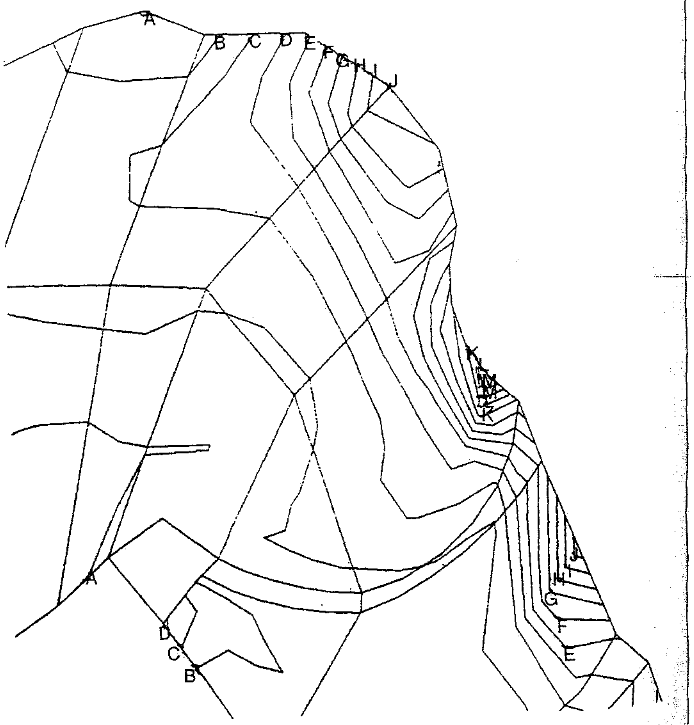

Fig. 4 *Von Mises stress contours in the higher stressed region (dorsal anterior part of talus) of the two-dimensional model of the normal foot during push-off; A = 5·0, B = 10, C = 15, D = 20, E = 25, F = 30, G = 35, H = 40, I = 45, J = 50, K = 55, L = 60, M = 65, N = 70, O = 75, P = 80*

Complete paralysis of the EHL increases the stress by 6%. As the lines of action of the EHL and TA are nearly the same, the stresses in the dorsal anterior region of the talus are not significantly influenced by paralysis of the EHL and the corresponding increase in the compensating TA force.

3.2.2 *Mid-stance position:* results show that a complete paralysis of PL increases the maximum principal stresses occurring at the dorsal anterior part of the talus by 3–9% of the normal value (40·5 N mm^{-2}) for a 10% variation in mean muscle forces. Complete paralysis of the FHL produces in this model a 0·4–3·2% increase in stresses at the same region.

3.2.3 *Push-off position:* it is observed that the increases in the maximum principal stress at the dorsal anterior region of the talus, for paralysis of TP or PL, are in the order of 4·6–4·9% and 1·3–2·3%, respectively, of its normal mean value (83·5 N mm^{-2}). Even when both muscles are paralysed, the influence of the greater value of TS force (see Table 2) produces only a slightly higher stress (6–6·5%) of the mean maximum principal stress. Simulation of paralysis of all three muscles (TP, PL and FHL) makes the force exerted by the TS somewhat larger, as shown in Table 2, but again it results in only a small increase of 7% in the mean maximum principal stress.

3.3 *Leprotic foot*

The results are presented of the stress analysis on three typical leprosy subjects, with muscle paralysis and foot geometry changes due to foot deformities, caused by different degrees of tarsal disintegration. Fig. 5 shows the von Mises stress contours in the mid-stance phase for leprosy subject MLW, in an early stage of tarsal disintegration. The maximum principal stress of 73 ± 2·3 N mm^{-2} occurs in the lower (plantar) anterior part of the calcaneus adjacent to the compressed thin layer of cartilage. This stress is 150% higher than the corresponding mid-stance stress in a normal foot model. The adjacent cartilages also show a maximum principal stress of 30 N mm^{-2}, which is found to be 13 times higher than the normal cartilage stress.

The analysis of stresses during the push-off phase for the same subject shows a maximum principal stress of 119 ± 0·5 N mm^{-2} in the compressed thin portions of the cartilage (nearer to the anterior plantar part of the calcaneus), whereas in the adjacent calcaneal bone the stress decreases to a value of 35 N mm^{-2}. The alternating increase and decrease of high compressive stresses in mid-stance and push-off phases in the above regions, and also in the upper (dorsal) part of the cartilage between navicular and cuneiform, might be responsible for the upwards projection of the navicular (as shown in Fig. 2) in this subject.

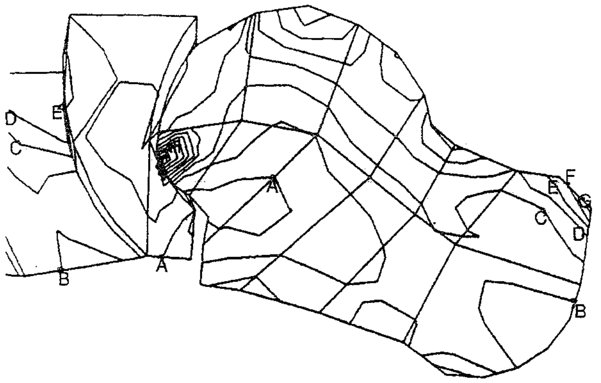

Fig. 5 *Von Mises stress contours in the higher stressed region of deformed right foot model of the leprosy patient MLW, with paralysed dorsiflexors, during mid-stance; A = 5·0, B = 10, C = 15, D = 20, E = 25, F = 30, G = 35, H = 40, I = 45, J = 50, K = 55, L = 60, M = 65, N = 70*

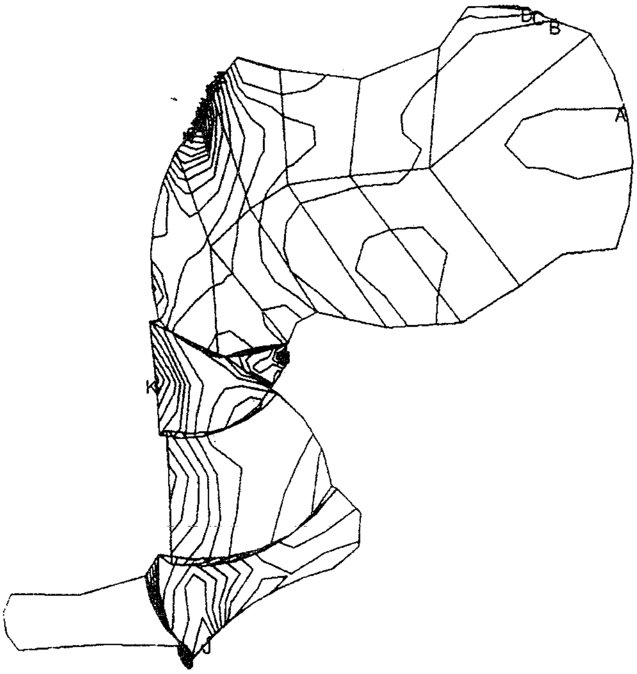

Fig. 6 *Von Mises stress contours in the deformed right foot model of the leprosy patient KTD, with paralysed dorsiflexors, during push-off; A = 5·0, B = 10, C = 15, D = 20, E = 25, F = 30, G = 35, H = 40, I = 45, J = 50, K = 55, L = 60, M = 65, N = 70, O = 75, P = 80*

In the second leprosy subject KTD, with an intermediate stage of tarsal disintegration, the analysis of stresses during mid-stance simulation shows the maximum principal stress to be 55·5 ± 0·5 N mm^{-2}, occurring in the dorsal posterior region of the navicular. The stresses in the push-off phase indicate three regions of high stress (Fig. 6); lower anterior metatarsal head, plantar and proximal part of navicular and dorsal anterior part of the talus. The maximum principal stress in the metatarsal head is found to be 82 ± 1 N mm^{-2}, which is

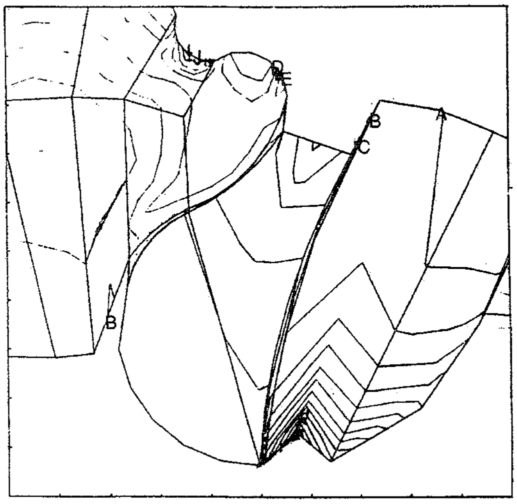

Fig. 7 *Von Mises stress contours in the deformed left foot model of the leprosy patient KLPS, with paralysed dorsiflexors, during push-off; A = 5·0, B = 10, C = 15, D = 20, E = 25, F = 30, G = 35, H = 40, I = 45, J = 50, K = 55, L = 60, M = 65, N = 70*

four times the stress value in the corresponding region of a normal foot model. The maximum principal stresses in the plantar proximal part of the navicular and dorsal anterior part of the talus are in the order of $83 \cdot 5 \pm 0 \cdot 5$ N mm^{-2}. The high stresses in the above regions could be responsible for the disintegration of the tarsal bones and may result in the deformed shape of the foot, as observed in the X-ray.

In the third leprosy patient KLPS, in an advanced stage of tarsal disintegration, the analysis of stresses during push-off simulation shows the maximum principal stress to be $73 \pm 1 \cdot 5$ N mm^{-2}, occurring at the downwards (plantarward) protruding posterior part of the metatarsal base (Fig. 7). It is interesting to note that this patient has an ulcer at the same spot.

4 Discussion and conclusions

It is found that in the articulated 2-D normal foot model the maximum principal stress occurs at the anterior dorsal part of the talus, bordering the cartilage between the talus and the navicular, in all three quasi-static walking phases. The maximum principal stresses for the articulated normal foot model during heel-strike, mid-stance and push-off are in the ratio 1 : 1·5 : 3·25. According to orthopaedic surgeons, arthrosis sometimes develops in the above-mentioned highly stressed regions of the talus. Simulation of complete paralysis of the tibialis anterior in heel-strike increases the maximum principal stress occurring at the toes by 2·3 times the corresponding stress in the normal articulated foot model. This result may indicate the impossibility of long toe extensors, like EHL, replacing the TA, which is why a person with TA paralysis walks with a flapping foot.

Simulation of paralysis of another single muscle in the mid-stance or push-off phase results in a small increase in the maximum principal stress in the talar region. The paralysis of muscles with a nearer insertion site with respect to the ankle joint (such as TA or TP) increases the stresses in the talar region more than the paralysis of muscles such as EHL or FHL. The stress analysis for leprosy subjects, as discussed above, shows the interesting combined effects of foot shape and muscle paralysis on the development of high stresses in certain regions of the foot. If the mechanical strength of the bone is reduced due to osteoporosis or cystic degeneration in these regions, these high stresses may possibly contribute to tarsal disintegration. Clinical findings also confirm that the navicular, talus and metatarsals in the above-stated regions of some leprosy patients undergo disintegration (KULKARNI *et al.*, 1985).

In this study a complete linear analysis was carried out using linear elastic material properties. Using a soft tissue pad under the foot skeleton introduces viscoelastic effects for which the finite element code used (GIFTS) is not very well suited. In the development of more appropriate models of the foot, an extension to three-dimensional models is perhaps more adequate than the introduction of soft tissue. Nevertheless, it is expected that in quasi-static analyses the effect of soft tissue is only noticeable on the plantar pressures between foot and ground.

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